

PHYSIOLOGICAL ASPECTS OF EVA

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INTRODUCTION

EVA operations have become increasingly complex since the days of Gemini. In the Space Station era, EVA is expected to involve 1000 to 4000 manhours per year. These EVA operations will include Space Station construction, servicing and maintenance, and payload servicing and maintenance. Crewmembers may accumulate as many as 250 hours EVA during a 90 day mission, considerably more than the 12 to 14 hours spent on Shuttle missions. Physiological parameters and operational variables of little or no concern on Shuttle EVAs may be a major concern for Space Station EVAs, since they may limit man's productivity, and thus impact EVA scheduling, tasks and safety.

There are several areas of concern which the physiologist in conjunction with the space suit designers must address in order to optimize EVA work. These areas include: (1) suit pressure and breathing gas composition, (2) metabolism requirements associated with work duration and rates, (3) body waste collection and storage, and (4) thermal balance/comfort. In this paper each of these topics is briefly discussed.

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DISCUSSION

Atmospheric Pressure. The limiting factor to providing a sea level pressure in the ^{space} suit has been suit technology. Thus for now, Space Station EVA will involve repeated decompressions by the EVA crewmembers. A preliminary analysis of EVA mission requirements conducted by Grumman as part of an Advanced EVA Systems Design (AEVAS) study show crewmembers performing one to five EVAs per week [1]. The Frequency of decompressions necessary to meet the proposed EVA work schedules must be considered in light of the potential short- and long-term hazards to the health of the EVA crewmembers. Furthermore, the effects of repeated decompressions on work performance, and the logistics cost in consumables attendant to airlock operations must also be assessed. The nature of repetitive decompressions on the formation of tissue gas bubbles, and the provocation of decompression sickness is not well understood. Little information exists on the effects of multiple decompression exposure (e.g., frequency, type and sequence of missions) on the development of decompression sickness and/or long-term consequences. The U. S. Air Force has found that the period of excusal from flying between missions and after altitude training flights must be long enough so that the pilot will not be at increased risk of developing bends when he is allowed to decompress for the second time, but short enough so that ground time is minimized. Adams, et al, showed an increased incidence of bends with less than 24 hours ground time between flights [2]. Waligora, et al, in another study indicated no significant increase in the incidence of bends after 17 hours ground time [3].

Persistence of asymptomatic bubbles has been noted for as long as seven days after decompression of humans in a hypobaric chamber. Repeat

exposures within the seven day period led to an increase in the incidence of decompression sickness [4]. In 1977, Furr presented data relative to the incidence of decompression sickness among U. S. Navy hypobaric chamber inside observers/instructors, as compared to trainees [5]. The instructors, who characteristically made two to three chamber flights per week, expressed symptoms of bends ten times more frequently than did the trainees. Jauchem, et al, noted significant changes in blood white cell counts, activated partial thromboplastin^m, urea nitrogen, uric acid, inorganic phosphate, potassium and osmolality, as well as changes in other organ systems in a study involving repeated decompressions simulating EVA for 3 days [6].

Space Suit Oxygen Levels. ~~Operational limits for Space Station EVAs will be largely determined by space suit technology.~~ Space suits will likely operate at pressures from 222 mm Hg (current state-of-the-art) to perhaps as high as 760 mm Hg. Physiological considerations favor a two-gas system (oxygen and nitrogen), but considerations of costs and complexity may lead to the selection of a simpler one-gas (pure oxygen) system. However, exposure to pure oxygen at high pressure creates problems. Clark and Lambertsen in 1971, and Lambertsen in 1978 [8], thoroughly reviewed the physiological and pathological degradation associated with hyperoxia [7,8]. Johnson in 1985 discussed the reduction of circulating red blood cell mass induced by hyperoxia [9]. The effects of breathing high partial pressures of ^oxygen for extended periods are complex (Fig. 1); tolerance being a function of the oxygen partial pressure, duration of exposure, and periodic return to breathing a normoxic atmosphere. Pulmonary and erythropoietic effects of hyperoxia appear to be the key parameters limiting long-term (90 day) EVA

productivity.

Space Suit Carbon Dioxide Levels. Human tolerance to CO₂ is determined by several factors, two of which are the concentration of inspired CO₂ and the duration of exposure. Acute effects of high concentrations of CO₂ are usually observed within the first several hours of exposure; whereas, chronic effects can take up to several weeks to be manifested.

In an early study of human tolerance to acute CO₂ exposure, White, et al, [10] exposed 31 men (21 to 43 years of age) to a 16 minute period at 6% CO₂. As a result of the exposure, respiratory rate, ^{and} ~~expiratory~~ volume and alveolar CO₂ concentration increased. In spite of these physiological changes, there was no decrease in ability to perform a card-sorting behavioral test. In addition, 8 of the subjects who were trained pilots, indicated that the 6% CO₂ level would not interfere with their ability to safely handle an airplane.

In a more recent study [11] breathing patterns were examined in 25 men and 5 women during 10 minutes of exposure to 2%, 3% and 4% CO₂. At these concentrations, there was an increase in minute ventilation due primarily to an increase in tidal volume rather than respiratory frequency. Although CO₂ tolerance was not assessed in this study, the subjects were able to easily withstand the increased CO₂ levels. In another study [12], 8 exercise-trained men were exposed to CO₂ levels of 8, 15, 21 or 30 mm Hg. ~~During CO₂ exposure,~~ the subjects engaged in 30 minutes of moderate and heavy exercise (1/2 and 2/3 maximum $\dot{V}O_2$ respectively). At 8 and 15 mm Hg, there were no apparent difficulties in performing the exercise. Higher CO₂ levels caused some discomfort, but not of sufficient magnitude to prevent the subjects from ^{performing the} ~~exercising~~.

Finally, in an exhaustive review ^{by} of NIOSH [13] many studies of CO₂ tolerance during exercise were conducted. The authors of the NIOSH publication ^{reported} ~~concluded~~ that the effects of CO₂ on metabolism and ventilatory responses were readily apparent only at CO₂ concentrations of at least 2.8% (0.41 psia). Furthermore, they concluded that "all grades of exercise, including exhaustive stress (250 W, 3.58 kcal/min above baseline) can be tolerated for at least 30 minutes at CO₂ concentrations of up to 4% (0.59 psia)" and "At or below 3.8% CO₂ concomitant with lower, but still strenuous levels of exercise (130-180 W, 1.86-2.58 kcal/min) no ill effects other than awareness of increased ventilation (no dyspnea reported) were experienced by the subjects." Thus, for ^{at} least 30 minutes, humans can apparently easily tolerate CO₂ levels of ^{at} least 2.8% even during strenuous exercise.

The effects of 30 to 42 days of continuous exposure to 1% and 2% CO₂ were studied in submarine crews during operations and in subjects under laboratory conditions [14, 15]. The effects of CO₂ exposure under these conditions included increases in minute ventilation, tidal volume, alveolar PCO₂, arterial PCO₂, O₂ uptake and physiological dead space. There is also a persistent respiratory acidosis and cyclic changes in pH that appear to be related to cyclic changes in CO₂ absorption from bone. These changes apparently did not interfere with the ability of the submarine crew or the laboratory subjects to perform various assigned tasks. Likewise, physiologic changes associated with 5 days of 3% CO₂ exposure were found not to be a serious challenge to human subjects. Indeed, at this level of CO₂, the body more readily adjusts to the CO₂ concentration than it does ^{to} lower levels of CO₂ [13].

Based on results from these studies of acute and chronic effects of

CO₂ exposure, CO₂ levels of at least 15.2 mm Hg (2%) and likely even 22.8 mm Hg (3%) would not have a detrimental effect on either the work performance or survivability of an astronaut during an 8 hour EVA. Consequently, during an 8 hour EVA, there is no reason to believe that a continuous CO₂ exposure of 10 mm Hg (i.e., less than 2%) would be detrimental to the health and performance capability of the astronaut.

Metabolic Requirements for Optimizing Work Duration and Rates.

Physiological adjustments to work are complex and involve all of the body's systems. Energy costs for various activities in the one-g environment have been studied extensively. In an early study by Dill [16], different types of work were classified according to metabolic demand. In this study an average 70 kg man performing moderate work (e.g., the intensity of work involved in most everyday tasks) will expend 1900 kcal/8 hr while working, 1400 kcal/8 hr while resting, and 500 kcal/8 hr while sleeping, for a total of 3800 kcal/day. This cycle can be sustained indefinitely without physiological degradation.

On the other hand, heavy work cannot be performed for long periods each day over an extended period. Heavy work involves the expenditure by a 70 kg man of up to 4300 kcal/hr and can cause oxygen consumption to increase as high as 1.8 l/min (i.e., the rate for walking at 3.5 mph up a 10% grade). The energy expenditure rate for a particular task has been shown to affect the efficiency of the work required to perform the task. Nearly 50 years ago Lupton [17] demonstrated that work efficiency changes as the rate of work changes (Fig. 2).

In performing moderate and heavy work, both aerobic and anaerobic metabolism are utilized. The capacity for anaerobic metabolism permits expenditure of more energy than could be derived from oxidative processes

alone. During heavy work, anaerobic capacity will determine the duration of the work period. In moderate work, anaerobic metabolism allows for the almost instantaneous release of required energy without the delay associated with aerobic metabolism. Finally, training can increase both aerobic and anaerobic capacity, resulting in an increase efficiency in performing work.

In addition to metabolic adjustments during work, there are significant changes in respiration and circulation (Fig. 3). Cardiac output will greatly increase during exercise, as venous return increases secondary to muscular and respiratory pumping. ~~In the one-g Earth environment, walking, running, and the increase expansion of the pleural cavity associated with increased respiration will effectively increase venous return to the heart.~~ On the other hand, static exercises (such as weight lifting) actually reduce venous return. Speed of recovery from fatigue is a prime factor in determining optimum work durations. and rates. Simonson [18] presented data demonstrating a logarithmic relationship between endurance and load for various types of work (Fig. 4). Fatigue recovery speed determines the relationship between endurance and load.

Some factors which affect work physiology may not change significantly in the EVA environment (for example, personality and motivational factors). Other factors are significantly different and must be assessed. For instance in the weightless environment, cardiac return and cardiac output are altered, and physical conditioning in general is affected.

Recent estimates imply that energy requirements in microgravity are slightly greater than in the normal gravity environment, but further studies are required before total energy needs can be reliably predicted

for long term spaceflight operations [19]. Furthermore, for EVA the inefficiencies inherent in working in a pressure suit constitute a major increase in total work required. These are important considerations in attempting to calculate optimum work rates and energy needs for the EVA crewmember since vital body stores of glycogen must be at an optimal level prior to EVA. Foods consumed during EVA must supply a readily available source of energy. The required food levels need to be established by studies to determine optimal work rates and energy expenditure. Figure 5, a summary of past EVA average metabolic rates, is an example of such a study.

In addition to these physiological factors, many operational factors also affect the duration, intensity and frequency of EVA work. Such factors include the quantity of consumables, the provision for suit servicing and personal hygiene, the complexity of tasks and the number, duration and scheduling of EVA events, the ^{potential}~~potential~~ for physical exhaustion and the available recovery time, and the training of EVA astronauts. These factors will affect physiological efficiency and cumulative metabolic demands. In short, the assessment of dietary requirements for EVA crewmembers requires an integrated treatment of all these factors.

Bergstrom, et al [20], showed that work time is increased in subjects on high carbohydrate diets (Fig. 6). Carbohydrate loading has been proposed for some military operations in which the combatants would be required to exert maximum physical activity for periods longer than normally expected. This may or may not be desirable for EVA. During moderate work, the proportions of carbohydrate and fat as fuel sources are about the same as at rest; but, as work intensity increases, carbohydrate

alone becomes the primary source of fuel. Exhaustion occurs when muscle glycogen stores are depleted and blood sugar levels drop (Fig. 7). Food requirements for EVA should be based on a high carbohydrate diet if it can be shown that EVA work is comparable to metabolic rates higher than that normally defined as "moderate work."

Dehydration can have severe effects on performance. When the amount of body water lost from sweating, respiration, etc is equivalent to ^{about 8%} ~~10%~~ of body ^{water} ~~weight~~, physical performance is impaired even though mental performance may ^{still} be unaffected. As more body water is lost, physical and mental performance ^a rapidly deteriorates. Death occurs when 20% to 25% of total body water is lost. In an early study, Nielsen [1] showed that sweating rate is dependent on work rate (Fig. 8). Furthermore, sweating is apparently independent of skin temperature; even with cooled skin, sweating can occur during work. Water and solute lost due to sweating must be replaced to maintain proper osmolality and electrolyte balance and thus maintain EVA efficiency.

The effect of various degrees of dehydration on EVA work needs to be carefully analyzed. ~~It is conceivable that~~ ^{some} crewmembers may elect to restrict water intake in order to not be bothered with the problem of urine collection and post-EVA cleanup.

Finally, the methods currently used to provide in-suit water and nutrients need to be re-evaluated, not only in terms of caloric and fluid requirements, but in engineering terms as well. There are alternative methods to current in-suit fluid and food storage and dispensing systems. For example, a liquid nutrient system replacing the current "food stick" concept may offer several advantages, one being the capability of tailoring the food to meet specific ^{dietary} ~~caloric, electrolyte, vitamin,~~

~~protein-fat-carbohydrate~~ requirements, and personal preferences (flavoring, sweetening, etc). The logistics of packaging, suit servicing, etc is another advantage of a liquid nutrient. The potential advantages and disadvantages of locating liquid containers (water and liquid nutrients) external to the suit enclosure needs to be assessed. Servicing and reliability may be enhanced by installing these containers in the "backpack," and incorporating quick disconnects for replenishment and manual override valves for controlling flow into the suit enclosure.

The choice of in-suit feeding versus returning to the airlock for a lunch break is another issue relevant to ~~feeding during~~ EVA. The dominant factor mitigating against a lunch break is the associated increase in EVA overhead (non-productive hours) which is already ^{✓ 575}underscrably high as shown in Fig. 9. The translation between the work site and the airlock, the extra cycle of hatch operations, recompression and decompression, the break in suit integrity, and the extra suit checkout that must be accomplished will collectively increase the overhead by an estimated 1 hour and 15 minutes [/]. The added time might also extend the total duration of the EVA beyond acceptable limits in terms of crew fatigue, ~~atelectasis, etc.~~ The airlock operation also requires additional power for pumpdown and involves a small lost of consumables. On the other hand, the factors in favor of a lunch break include (1) inadequate volume in the suit to accommodate the necessary quantity of food and water, (2) the added complexity and risk of spills associated with in-suit feeding, and (3) the fact that inadequacies in the suit waste collection system may necessitate a break, independent of food and drink requirements.

Waste Collection & Management. During EVA, the capability for

collecting and storing urine, feces and possibly vomitus will be important to the comfort and performance of the crewmember. The proposed duration of EVAs (up to 8 hours) will necessitate space suit waste storage capacities not required during the relatively short EVAs of the Gemini, Apollo and Shuttle programs.

In addition to causing minimal discomfort, in the space suit there should be no contamination of other suit subsystems such as the air supply or the drinking water supply. Astronauts may experience space motion sickness during EVA, and collection devices should be large enough to contain predicted volumes of vomitus. Finally, pre-EVA diets designed to minimize fecal production should be considered; however, these diets may adversely effect the caloric needs of a crewmember performing numerous EVAs during a 90 day mission. Thus, diets to reduce fecal production must be considered carefully.

Current Space Station plans include a space suit with a 1000 ml capacity for urine collection. This capacity may dictate the pre-EVA water provision as well as the intensity and duration of EVA tasks. In addition, the microgravity-induced changes in body fluid distribution and rate of digestion will surely have an impact on urine formation during EVA early in the mission.

Thermal Balance & Comfort. Understanding thermoregulation in EVA crewmembers is important to understanding limits to EVA work. Thermoregulation can be modeled after a ^Proportional controller; that is, the response of the system will be in proportion to the intensity of the thermal stress [12]. If however, thermal stress is of sufficient intensity, thermoregulatory mechanisms may be unable to maintain normal

thermal
body temperature. Results of ¹experiments ~~on vision~~, for example, *have* demonstrated that deviations in core temperature of as little as one degree *centigrade* can have a detrimental effect on ^{visual} performance (Fig. 10) [18].
As work intensity increases, heat tolerance decreases. The ability of the space suit cooling system to handle heat generated during EVA will contribute to the limits for effective EVA work. The proposed space suit thermal regulatory system will handle metabolic rates from 250 BTU/hr to ⁶1000 BTU/hr for at least 8 hours and peaks of ²⁰1600 BTU/hr for ^{just a few minutes} ~~1~~ hour. The present planned limitation to body heat storage is 300 BTU.

Heat production during moderate work can range from 800 to 1600 BTU/hr. Heavy work can produce as much as 2000 BTU/hr, and at the highest continuous work loads, heat production can be as high as 2400 BTU/hr. If the space suit can dispose of a maximum of only 1600 BTU/hr (including loss due to suit leakage), then a significant thermal load (i.e., greater than the 300 BTU allowed) could be imposed on an EVA crewmember performing ¹heavy work. Plans for limiting EVA work to a maximum of 1600 BTU/hr may be unrealistic; for, although it would be difficult to sustain this rate for any significant period, emergencies and other contingencies may develop where a work rate of 2400 BTU/hr would be required for a short period.

CONCLUSIONS

~~Man evolved to be a terrestrial animal; thus,~~ ^{man is} when placed in the space environment it is necessary to: (1) provide him with a near Earth normal environment, or (2) support his physiological functions, or (3) limit his activities such that ~~some~~ ¹physiological tolerance limits are not exceeded as the result of his altered environment and activities in that

environment. Within limits, man can adapt to a changing environment without a significant loss of performance. The problem for the physiologist studying the physiology of EVA is to determine the limits of adaptation to the space environment within the context of some defined, measurable parameters of work performance;^(A) In this paper, we have addressed some of the factors that must be considered in defining these parameters. These factors include constraints on performance due to limited quantities of oxygen, food and water, limited waste storage capacity, and limited capacity for heat removal and storage associated with space suit design. In addition, we have considered the effect on work performance associated with predicted changes in metabolism, oxygen and carbon dioxide levels and thermal balance during EVA work. Given the present-day paucity of physiological data on EVA work, this list of operational and physiological factors relevant to EVA work is only preliminary. However, the factors identified in this paper should provide a basis for more detailed studies of human performance during EVA work.

(A) or, define the change in performance when given an altered environment as the independent variable.

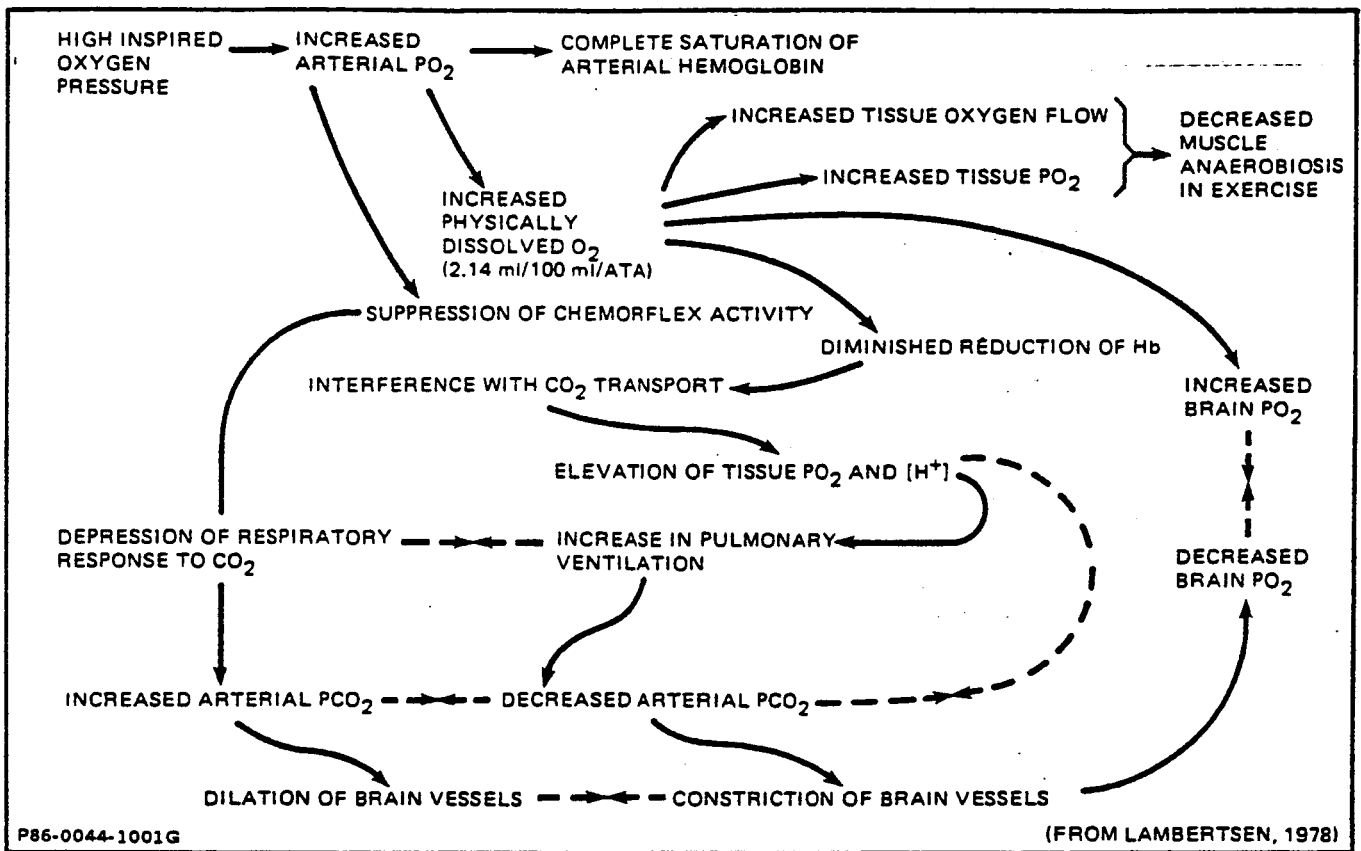


Fig. 2-2 Sequence of Acute Physiological Effects of Oxygen in Normal Men

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2.2.4 Optimum Work Duration & Rates (SOW 2.4)

2.2.4.1 Work Physiology - General Considerations - Physiological adjustments to work are complex and involve all of the body's systems. Energy costs for various activities in normal

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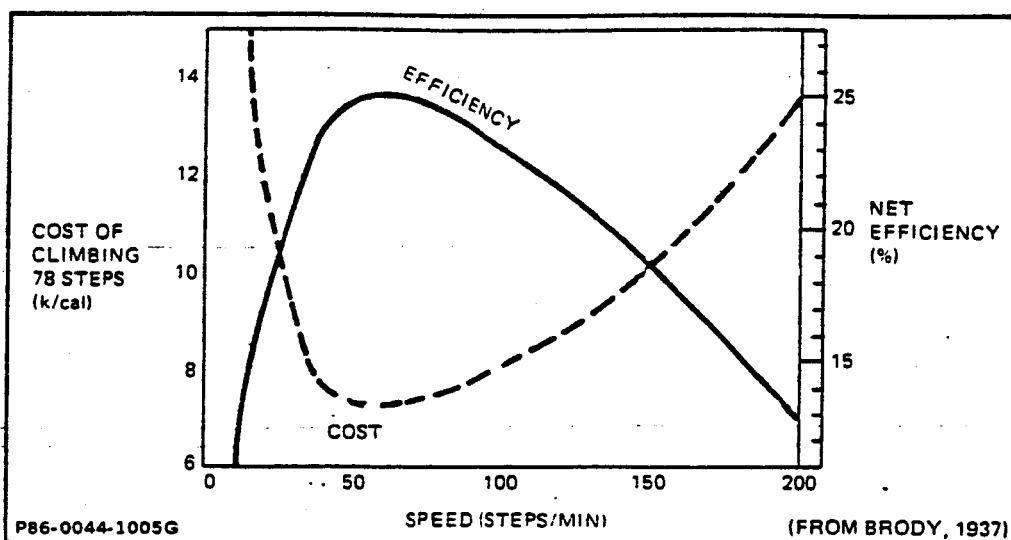


Fig. 2-6 Influence of Speed of Climbing Stairs on Energy Cost & Efficiency

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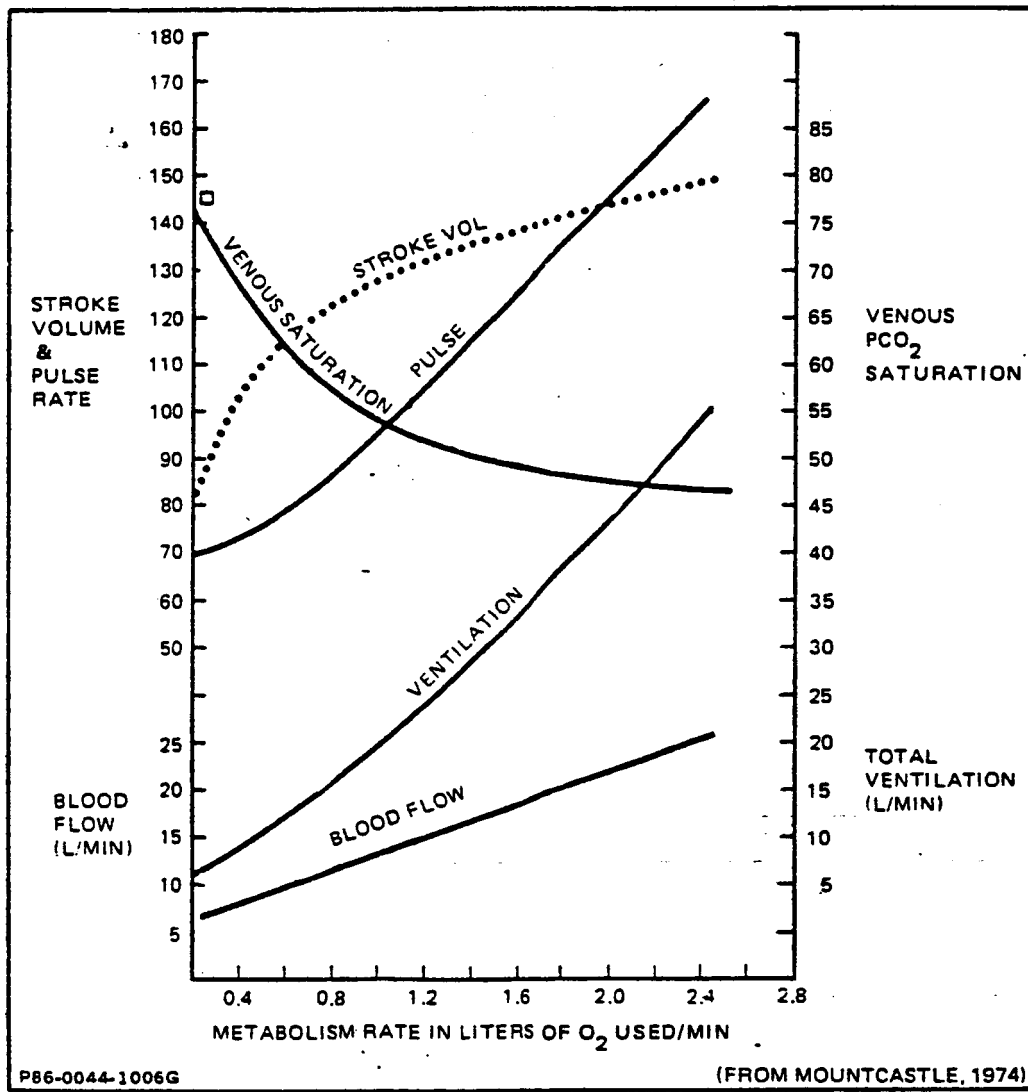


Fig. 2-7 Circulatory & Respiratory Changes of Man in Relation to Increments in O₂ Consumption Produced in Experiments at Different Intensities of Work on Bicycle Ergometer

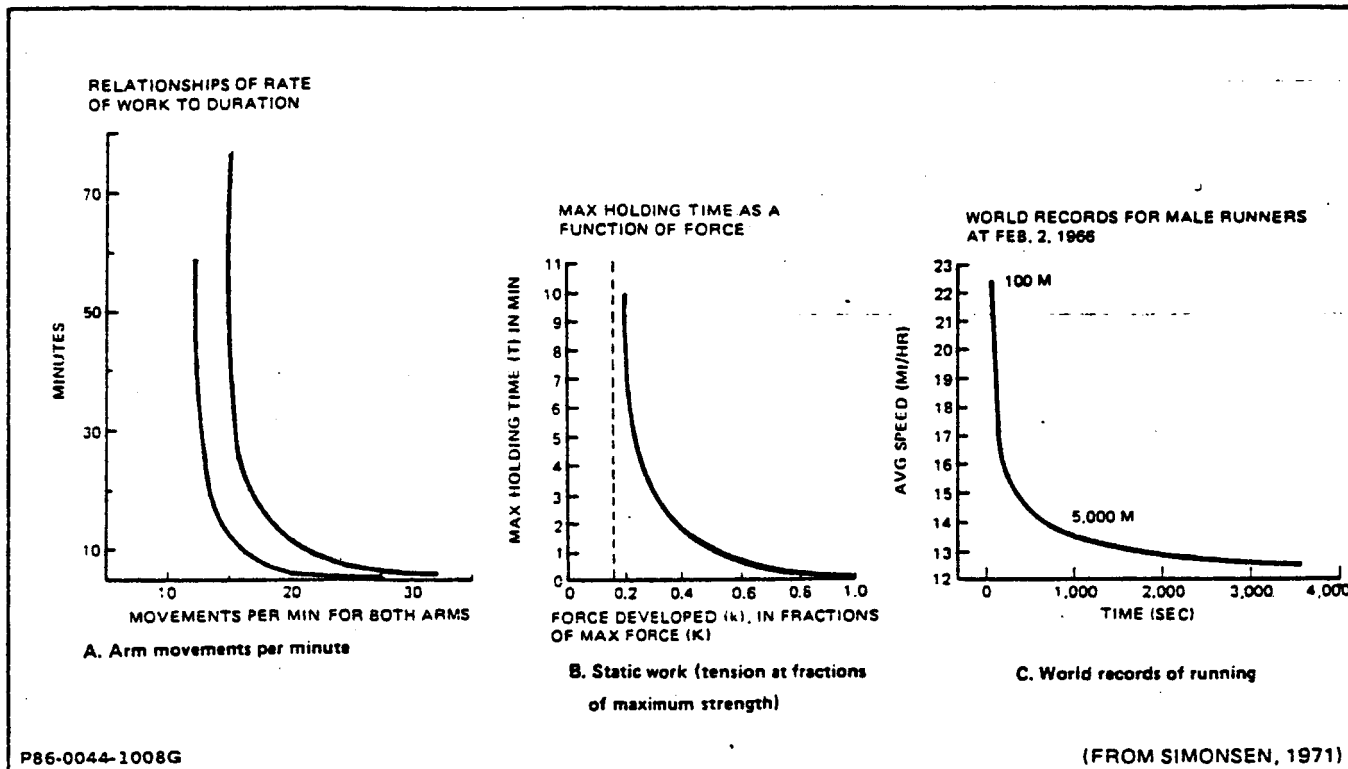


Fig. 2-8 Endurance & Intensity in Three Types of Work

2.2.4.2 EVA Work - Some factors which affect work physiology may not change significantly in

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recovery time, and the training of EVA astronauts all affect physiological efficiency and stamina.

MISSIONS	METABOLIC RATES (kcal/h)*	DURATION (h)
APOLLO	242 ⁺	0.5 - 1.5
SKYLAB	230	0.5 - 7.0
SHUTTLE	196	3.0 - 7.0
• BASED ON OXYGEN CONSUMPTION + ZERO-g EVAs ONLY P86-0044-1007G		

Fig. 2-9 Summary of Average Metabolic Rates during Space Mission EVAs

tive metabolic demands. In short, the assessment of dietary requirements for EVA crewmembers requires an integrated treatment of all these factors.

~~Our study will define the pertinent interactive effects of the physiological and operational factors. Our approach will include a review of information relative to augmenting endurance, minimizing strength reduction associated with microgravity exposure, and reducing fatigue recovery time. For example, in Subsection 2.2.2.1 we discussed carbohydrate loading as a means to enhance~~

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DIET	CARBOHYDRATE	MIXED	FAT-PROTEIN
WORK TIME (BICYCLE ERGOMETER)	166.5 ± 17.8	113.6 ± 5.3	56.9 ± 1.7
% MUSCLE GLYCOGEN, REST	3.31 ± 0.30	1.75 ± 0.15	0.63 ± 0.10
AFTER WORK	0.43 ± 0.06	0.17 ± 0.05	0.13 ± 0.05
BLOOD GLUCOSE mg%, REST	91.7 ± 5.9	76.8 ± 4.0	84.3 ± 4.0
BLOOD GLUCOSE mg%, WORK	63.3 ± 2.1	53.8 ± 6.2	50.7 ± 10.8

NOTE: CONDENSED FROM TABLE III, BERGSTROM *ET AL.*, 1967
P86-0044-1002G (FROM BERGSTROM, 1967)

Fig. 2-3 Mean Changes of Muscle Glycogen & Blood Glucose after Work

combatants would be required to exert maximum physical activity for periods longer than normally expected. This may or may not be desirable for EVA. During moderate work, the proportions of carbohydrate and fat as fuel sources are about the same as at rest, but, as work intensity increases, carbohydrate alone becomes the primary source of fuel. Exhaustion occurs when muscle glycogen stores are depleted and blood sugar levels drop (Fig. 2-4). Food requirements

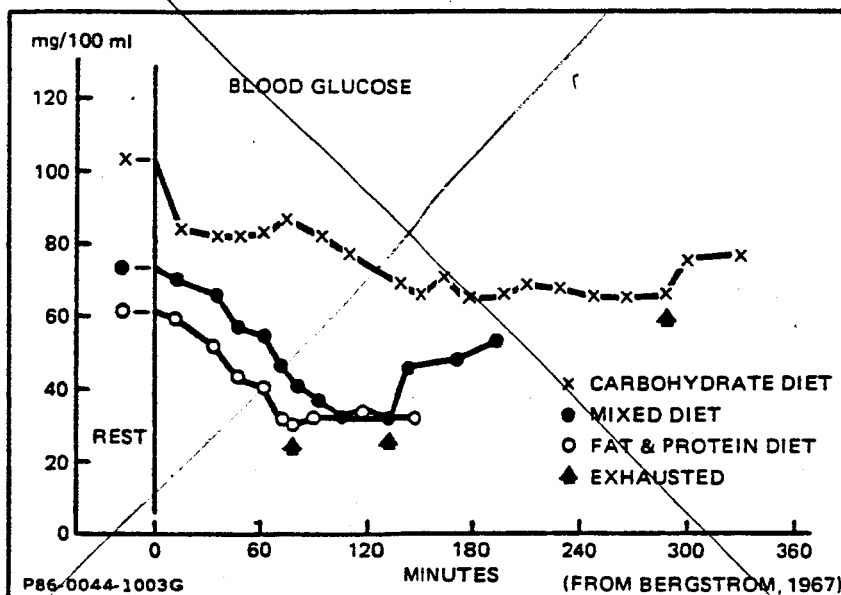


Fig. 2-4 Blood Glucose Concentration in Connection with Exercise after Different Diets

are considered; in Subsection 2.2.5, the need for in suit feeding versus taking a lunch break is discussed.

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2.2.2.1 Food Requirements - For the proposed study, we will review the information bases to analyze the food requirements that will maximize muscle fuel stores, and optimize electrolytes and great caloric (Fig.

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increases, carbohydrate alone becomes the primary source of fuel. Exhaustion occurs when muscle glycogen stores are depleted and blood sugar levels drop (Fig. 2-4). Food requirements

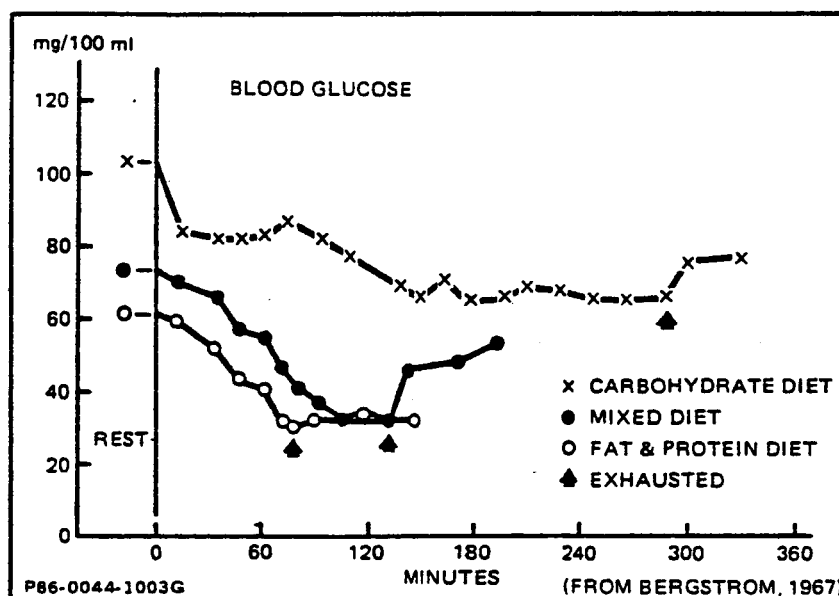


Fig. 2-4 Blood Glucose Concentration in Connection with Exercise after Different Diets

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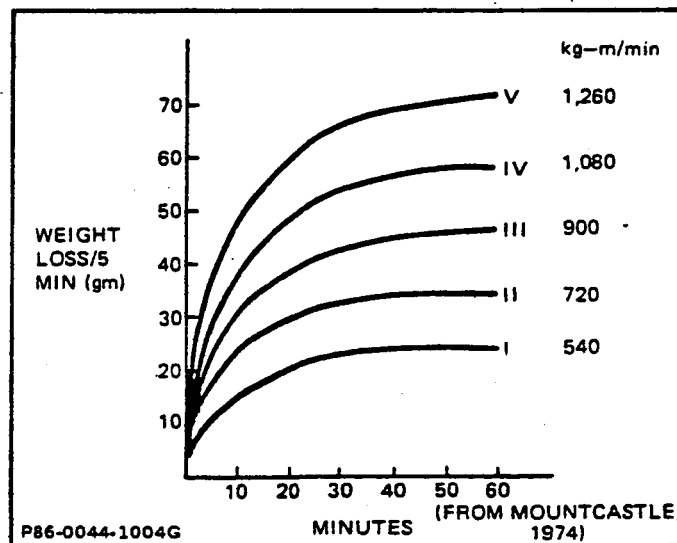


Fig. 2-5 Sweat Rate (Measured as Weight Loss/5 Min) in a Subject at Five Different Work Loads

The effect of various degrees of dehydration on EVA work needs to be carefully analyzed. It is conceivable that some crewmembers may elect to restrict water intake in order to not be bothered with the problem of urine collection and post-EVA cleanup. In the proposed study, we will evaluate the quantity of water required to prevent serious dehydration due to both sensible and insensible water loss during EVA by analyzing the intensity, duration and frequency of proposed EVA work within the limitations stated in the SOW. In addition, we will review the effect on EVA

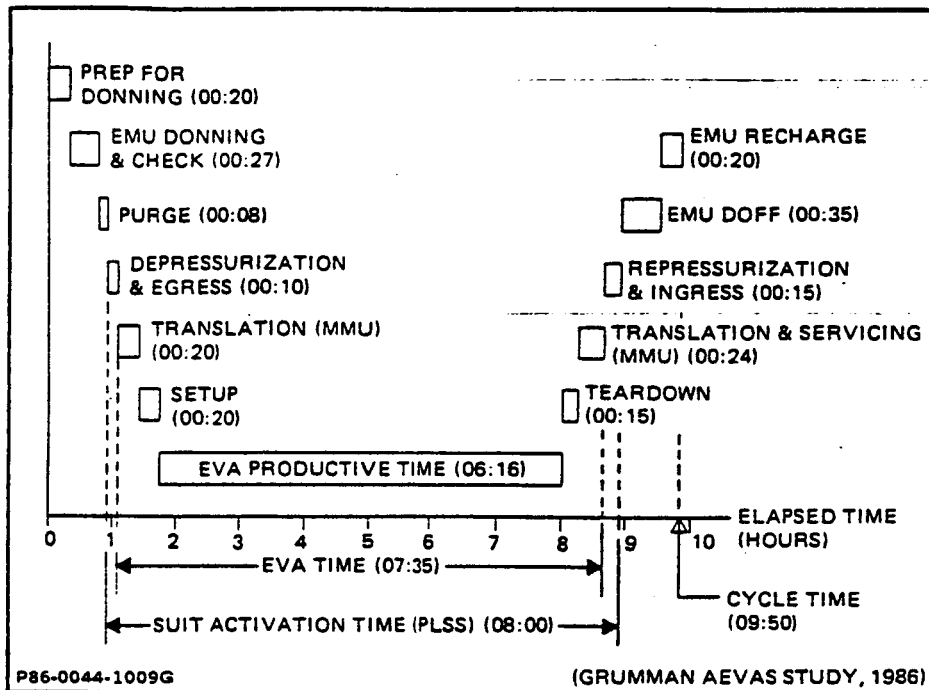


Fig. 2-10 Maximum EVA Productive Time with 8 Hr PLSS Capability

water, (2) the added complexity and risk of spills associated with in-suit feeding, and (3) the fact that inadequacies in the suit waste collection system may necessitate a break, independent of food and drink requirements.

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portional controller. That is the response of the system will be in proportion to the intensity of the thermal stress. If however, thermal stress is of sufficient intensity, thermoregulatory mechanisms may be unable to maintain normal body temperature. Results of experiments on vision, for example (Fig. 2-11), demonstrate that deviations in core temperature of as little as 1 °C can have a detrimental effect on performance.

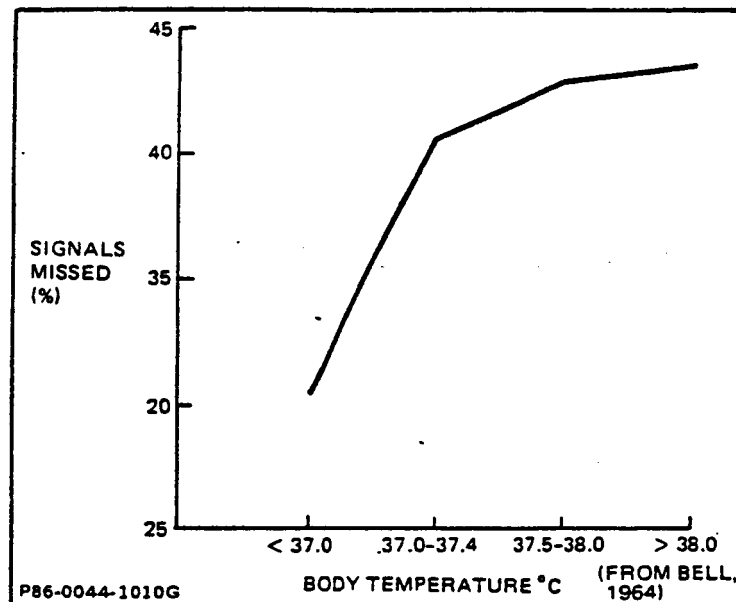


Fig. 2-11 Decrement in Performance on a Visual Task as a Function of Body Temperature (8)

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